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Heterodyne Lidar for Chemical Sensing

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ABSTRACT

The overall objective is to assess the detection performance of LWIR (long wavelength infrared) coherent Lidar systems that potentially possess enhanced effluent detection capabilities. Previous work conducted by Los Alamos has demonstrated that infrared Differential Absorption Lidar (DIAL) is capable of detecting chemicals in plumes from long standoff ranges. Our DIAL approach relied on the reflectivity of topographical targets to provide a strong return signal. With the inherent advantage of applying heterodyne transceivers to approach single-photon detection in LWIR, it is projected that marked improvements in detection range or in spatial coverage can be attained. In some cases, the added photon detection sensitivity could be utilized for sensing "soft targets", such as atmospheric and threat aerosols where return signal strength is drastically reduced, as opposed to topographical targets. This would allow range resolved measurements and could lead to the mitigation of the limiting source of noise due to spectral/spatial/temporal variability of the ground scene. The ability to distinguish normal variations in the background from true chemical signatures is crucial to the further development of sensitive remote chemical sensing technologies.

One main difficulty in demonstrating coherent DIAL detection is the development of suitable heterodyne transceivers that can achieve rapid multi-wavelength tuning required for obtaining spectral signature information. LANL has recently devised a novel multi-wavelength heterodyne transceiver concept that addresses this issue. A 5-KHz prototype coherent CO₂ transceiver has been constructed and is being now used to help address important issues in remote CBW agent standoff detection. Laboratory measurements of signal-to-noise ratio (SNR) will be reported. Since the heterodyne detection scheme fundamentally has poor shot-to-shot signal statistics, in order to achieve sensitive detection limits, favorable averaging statistics have to be validated. The baseline coherent DIAL detection sensitivity that can be achieved averaging multiple laser pulses and by comparisons of different wavelengths will be demonstrated. Factors that are presently limiting performance and attempts to circumvent these issues will be discussed.

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BACKGROUND/OBJECTIVE

The overall objective of this effort is to assess the detection performance of LWIR (long wavelength infrared) coherent Lidar systems that potentially possess enhanced effluent detection capabilities. Previous work conducted by Los Alamos has demonstrated that infrared Differential Absorption Lidar (DIAL) is capable of detecting chemicals in plumes with good sensitivity from long standoff ranges. Our DIAL approach relied on the reflectivity of topographical targets to provide a strong return signal while sacrificing any information regarding the range to the chemical plume. In principle a DIAL determination of a chemical absorbance can be accomplished with only two wavelengths, one within the absorption band and one outside the band to establish a reference return. However, in practice many wavelengths are desirable to help deal with multiple chemicals, atmospheric absorptions, and spectral variations in background albedo. One the advances resulting from the Los Alamos effort was the incorporation of acoustic-optic tuning elements within the CO₂ laser cavity. This allows random selection of different laser lines at repetition rates as high as 100 KHz. In this way, the entire wavelength spectrum accessible to the laser can be fully scanned before significant changes in the chemical plume or background occur.

With the inherent advantage of applying heterodyne transceivers to approach single-photon detection in LWIR, it is projected that marked improvements in detection range or in spatial coverage can be attained. More importantly, the added photon detection sensitivity could be utilized for sensing "soft targets", such as atmospheric and threat aerosols where return signal strength is drastically reduced relative to topographical targets. This would allow range resolved plume measurements and could lead to the mitigation of the limiting source of noise due to spectral/spatial/temporal variability of the ground scene. The ability to distinguish normal variations in the background from true chemical signatures is crucial to the further development of sensitive remote chemical sensing technologies.

FREQUENCY-AGILE HETERODYNE DETECTION

Heterodyne detection of Lidar returns is not new; it was first demonstrated in the 1960's using CO₂ lasers, exploiting their inherently narrow linewidth. The primary application was the detection of optical radar returns from hard body targets. In general, only a single wavelength was required for this application, in contrast to the many wavelengths desirable for DIAL applications. This requirement for many wavelengths has limited the use of heterodyne detection for chemical sensing applications. Traditional heterodyne detection approaches employ a separate local oscillator for each wavelength but this approach is problematic when many wavelengths are desired. LANL has recently devised a novel multi-wavelength heterodyne transceiver concept that addresses this issue.

A 5-KHz prototype coherent CO₂ transceiver has been constructed and is now being used to help address important issues in remote CBW agent standoff detection. A schematic diagram of the coherent CO₂ transceiver is shown in Figure 1. As in our direct detection DIAL apparatus, wavelength tuning is accomplished by a pair of acousto-optic modulators (AOMs) driven at the proper frequency for each laser line with pulsed rf from a frequency synthesizer. However, for the heterodyne transceiver, a small portion of the intracavity beam is extracted after passing through only one of the AOMs.

A typical CO₂ laser pulse consists of a short 100-200 ns spike followed by a longer low intensity tail lasting for several microseconds. The relative intensity of the spike versus the tail, as well as the length of the tail, are dependent on the gas composition and pressure in the laser. In our heterodyne transceiver, this long tail serves as the local oscillator and is combined with the return signal on a cooled HgCdTe (MCT) detector. Since the tail is part of the same pulse that was propagated to the target, it should be identical in frequency and phase. Furthermore, since the spike and the local oscillator tail are inherently linked, the laser line can still be randomly selected for each laser shot. The typical tail duration of several microseconds limits the operational range of this transceiver approach to perhaps 0.5 km.

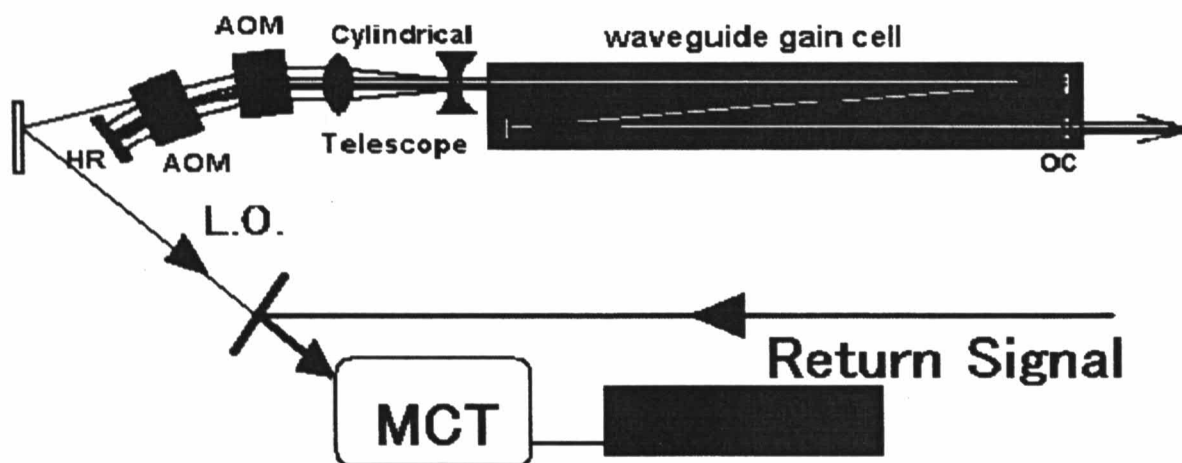


Figure 1. Schematic diagram of heterodyne transceiver

The photograph in Figure 2 shows the layout of the actual components. The beam path indicated in yellow is the intracavity beam. The beam serving as the local oscillator is extracted after passing through only one AOM as shown in blue. Because of this, the frequency of this beam is shifted by roughly 80 MHz from the primary laser beam. This shift is the basis for the heterodyne intermediate frequency. Furthermore, the intensity of this secondary beam is measured with a separate HgCdTe detector operated at room temperature. The intensity is used to drive active frequency stabilization circuitry, which in turn provides phase control of the AOMs and stabilizes the longitudinal laser mode for the cavity.

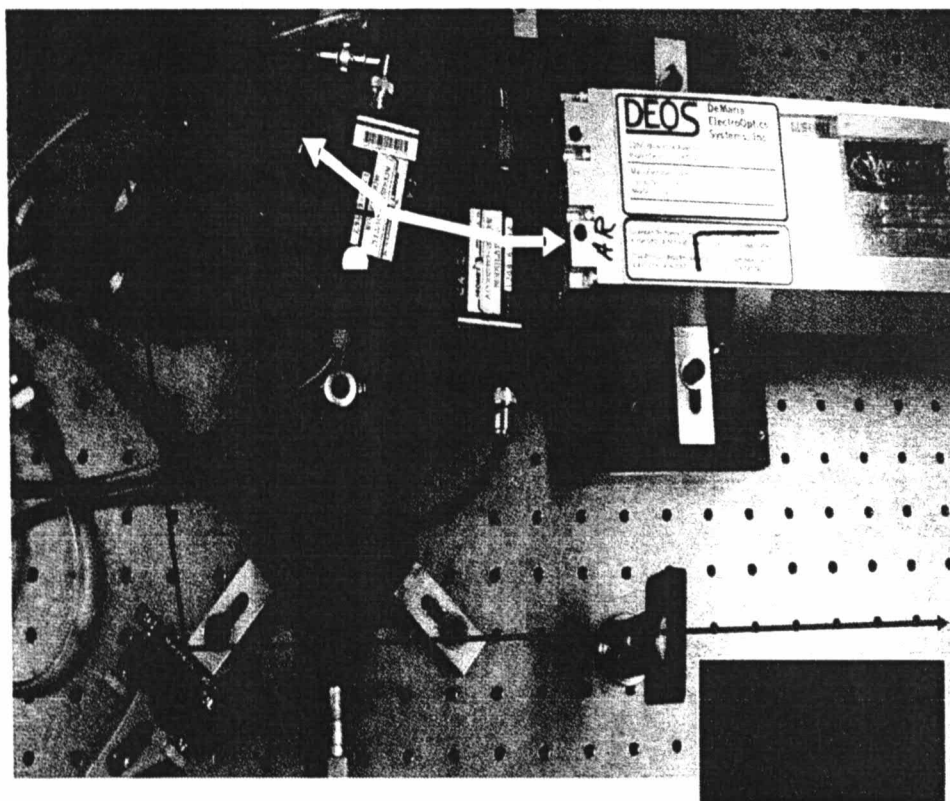


Figure 2. Photograph of heterodyne transceiver with beam paths indicated

A block diagram of the signal processing layout is shown Figure 3. The return pulse is overlapped with the local oscillator (tail pick off) on the cooled HgCdTe (MCT) detector. The resulting signal is amplified and passed through a 50-100 MHz band pass filter to select the component at the intermediate frequency. This is then rectified and integrated with a low pass filter to yield an intensity pulse. Figure 4 displays typical signal waveforms at different points with the signal processing electronics.

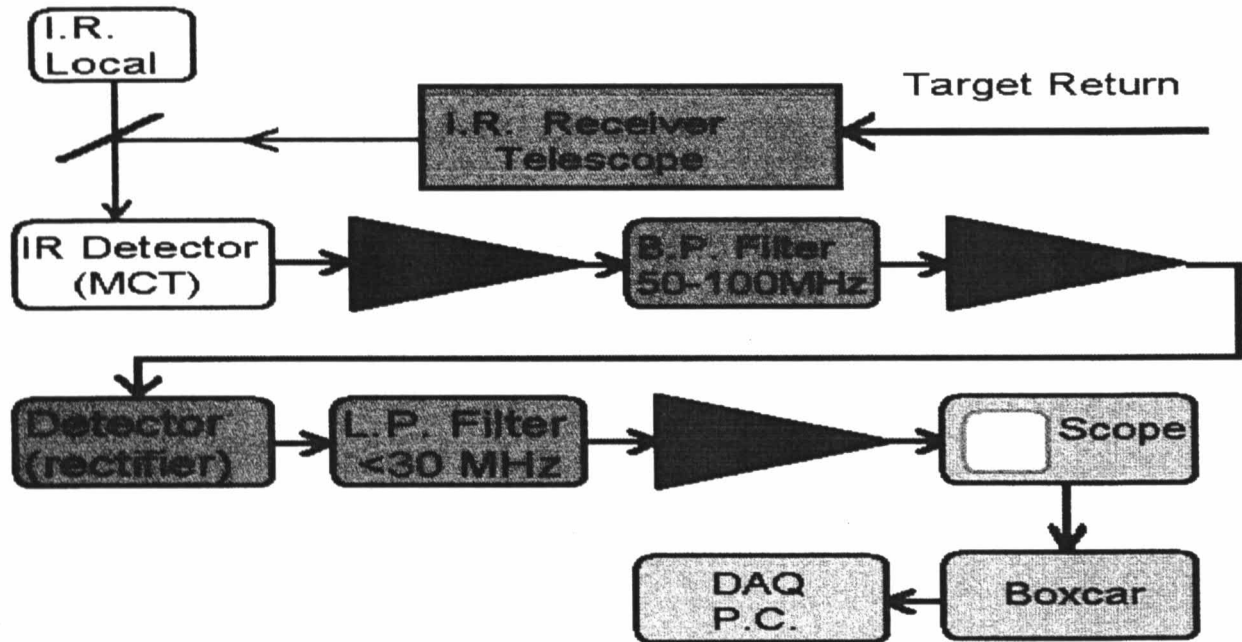


Figure 3. Block diagram of signal processing layout

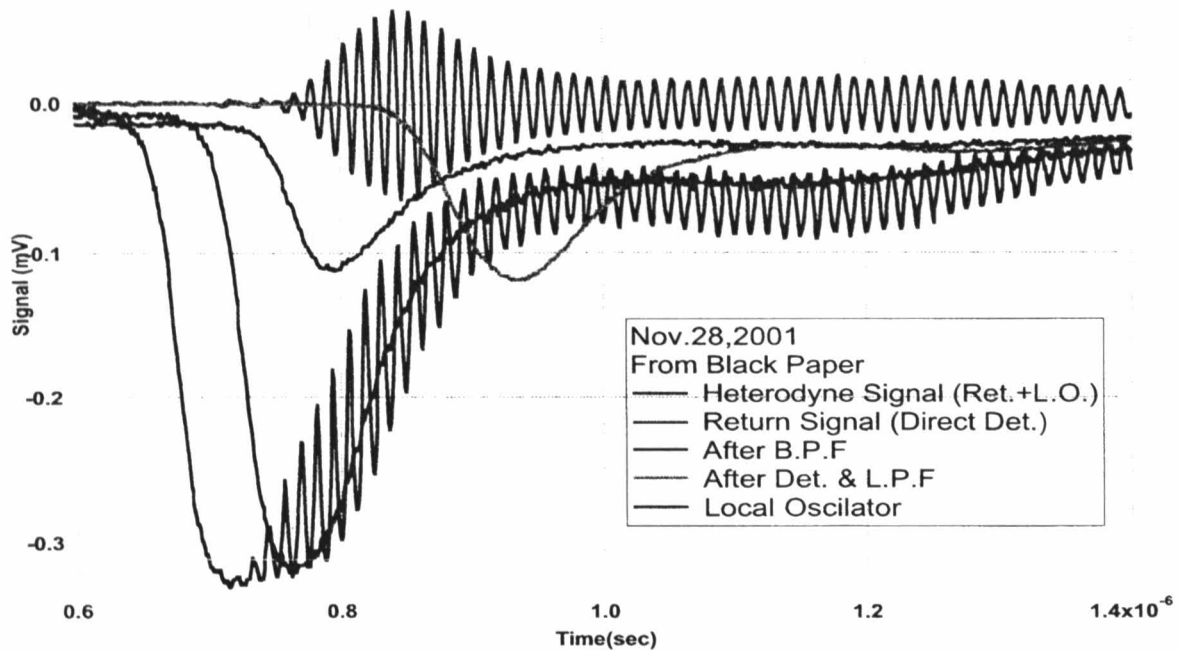


Figure 4. Typical signal waveforms

DEMONSTRATION OF CHEMICAL DETECTION

This heterodyne transceiver design should be well suited for chemical detection, given that the laser line wavelength can be randomly selected for each shot. To demonstrate chemical detection, the laser was operated at 5 KHz and sequenced through four different lines, namely 9P20, 9R20, 10P20, and 10R14. The return signal reflected off a sheet flat black paper was monitored using the heterodyne detector. A small amount (not determined) of Freon gas, tetrafluoroethene, was sprayed in the laser beam path. Figure 5 shows the result of this simple demonstration. The Freon does not attenuate the 9P20 line, but the other three wavelengths are each partially absorbed. The 9P20 line actually showed an increase in transmission, as shown in Figure 5. This is presumably due to an artifact of the simple experimental set-up; perhaps the gas altered the position of the return beam so as to improve the collection effectiveness of the receiver. The identity of the gas absorber can in principle be determined from the spectral pattern of the differential absorption, while the concentration*pathlength product can be determined by the magnitude of the absorbance.

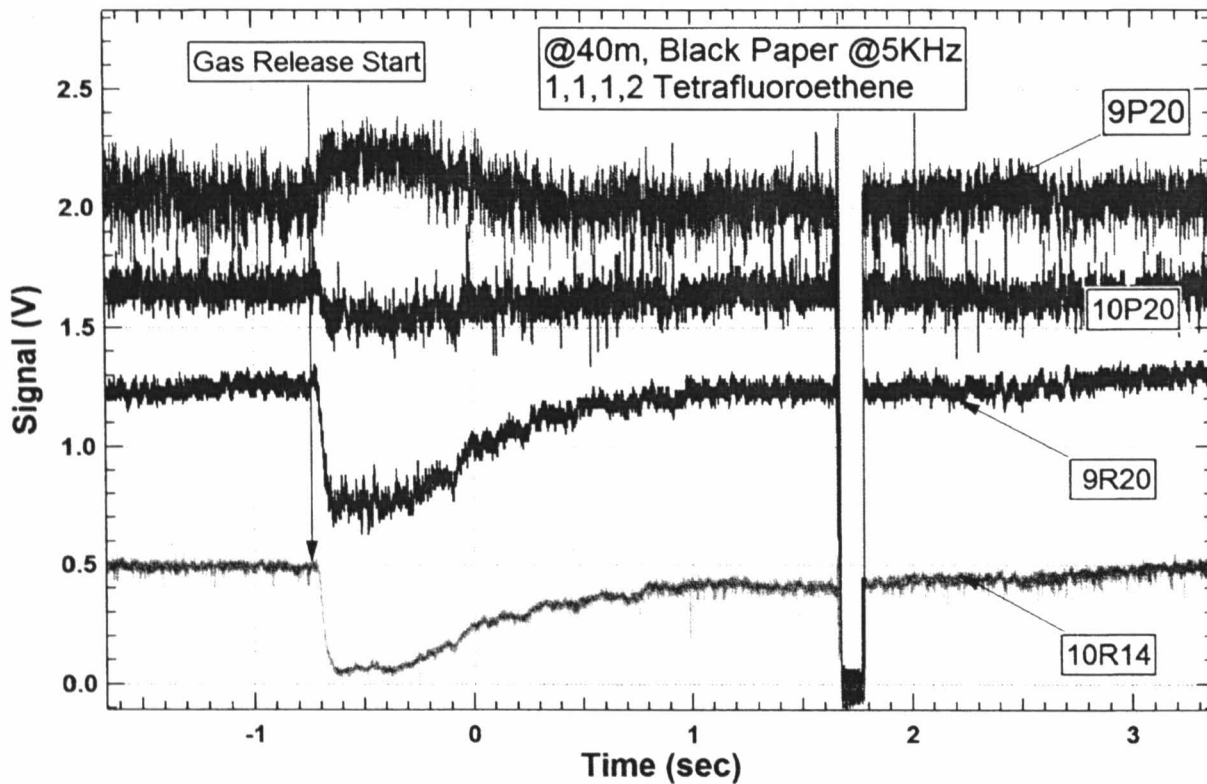


Figure 5. DIAL measurement of Freon gas using heterodyne transceiver

SIGNAL AVERAGING STATISTICS

A heterodyne detection scheme fundamentally has poor shot-to-shot signal statistics. The inherent single shot Signal-to-Noise Ratio (SNR) for a heterodyne transceiver is on the order of unity. To measure an absorbance of say 1% using DIAL ($\text{SNR} = 100$) therefore requires the averaging of at least 10^4 shots. Favorable averaging statistics have to be validated if a useful DIAL capability is to be realized.

To evaluate the averaging statistics, data runs are completed in which the return signal is recorded for several million laser shots. Targets include diffuse disks, which are rotated to simulate albedo variations, as well as specular mirrors. As noted before, the laser output energy is simultaneously recorded using room temperature HgCdTe detector. The heterodyne-detected return signal is ratioed against the laser output power on each shot to compensate for variations in the laser energy.

For each data run, the shots are binned into groups of a selected size. The average signal strength is calculated for each bin, and then the standard deviation among the bin averages is estimated. This procedure is repeated for various bin sizes. Figure 6 shows the result of a typical analysis of the return signal from a rotating diffuse target.

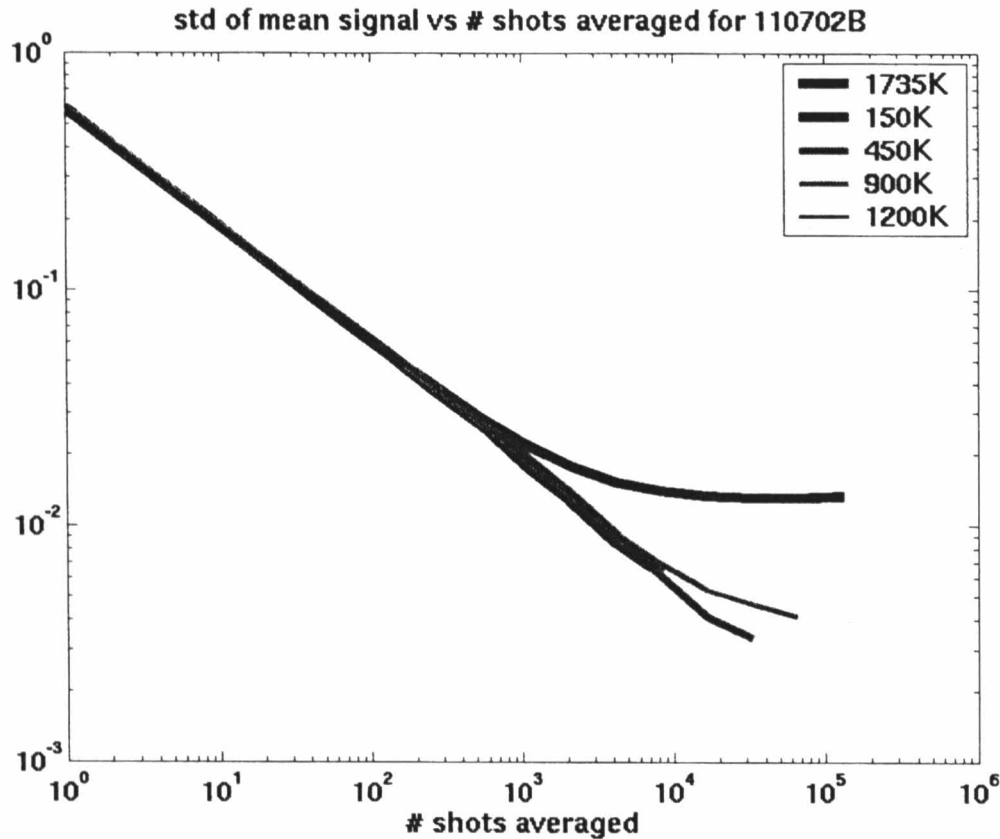


Figure 6. Standard deviation for the mean signal versus the number of shots averaged

The standard deviation of the mean signal is plotted versus the bin size, i.e., the number of shots averaged. If the noise were truly random, the averaging statistics would be expected to track the square root of the number of shots averaged (\sqrt{N}). The red line in Figure 6 shows the result when this analysis is applied to the first 150,000 shots. Good \sqrt{N} behavior is observed. This is also true when the procedure is extended to include the first 450,000 shots, as shown in green. However, as more shots are processed, deviations from \sqrt{N} behavior become apparent.

To help elucidate this behavior, the individual signals for this same data run are examined in more detail in Figure 7. A 10,000 shot running average is plotted. The red trace is the outgoing laser reference, the green trace is the heterodyne signal from the return beam, and the blue trace is the ratio (signal/reference). Several interesting observations are apparent in this figure. First, the reference and the signal are poorly correlated; ratioing the signal to the reference power does little if anything to reduce the signal drift. Second, the signal drifts about one percent for every 300,000 shots. Hence, averaging 300,000 shots is no better than averaging 10,000, and in fact could be worse. If data runs longer than this are processed, \sqrt{N} averaging statistics will not be followed because of the observed drift in the heterodyne signal intensity.

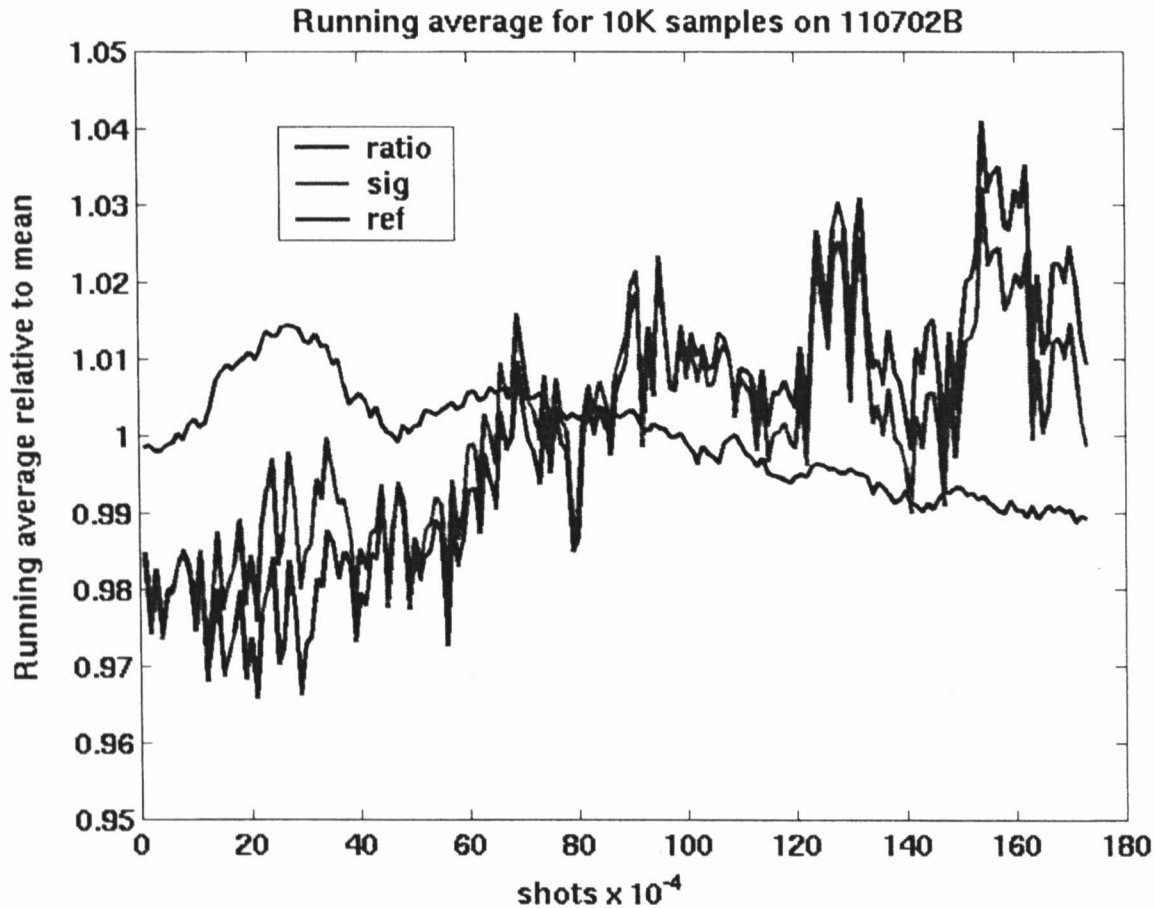


Figure 7. Running average (10,000 shots) of reference, signal, and ratio, relative to the mean, for same data run as displayed in Figure 6

To routinely achieve an effective $\text{SNR} \geq 100$ requires that the source of the signal drift be identified and mitigated. A possibly related issue is the lack of correlation between the signal and the reference. The reference detector measures the laser energy on each laser shot. In contrast, the heterodyne signal is the product of the return pulse and the local oscillator. Hence, the heterodyne signal depends on much more than just the overall laser energy. It depends on the energy in the spike, the energy in the tail (which does not necessarily track the spike), the phase overlap, the mode overlap, the beam overlap, and pointing variations or drifts of both the LO and the transmitted beam. The coherent signal is also inherently more sensitive to the operating parameters of the systems and to the ambient conditions, such as temperature changes and air currents. The reference channel would be much more useful for normalization if it tracked more of these parameters.

The system was recently upgraded so that a second reference channel now looks at the heterodyne signal between the LO and the outgoing pulse. The signal channel is as before, i.e. the heterodyne signal between the LO and the return pulse. Since the timing of the outgoing and return pulses differ by the round trip transit time, the same detector is used for both measurements, eliminating the need for matched detectors. However, because of the inherently low SNR in the second reference channel, the first reference channel that measures the laser energy is still used to drive the cavity mode stabilization. Measurements are underway to determine the extent to which these enhancements improve the averaging behavior.

SUMMARY AND FUTURE PLANS

A novel frequency-agile heterodyne transceiver has been developed. Experiments show that it can be used for DIAL determinations of chemical plumes. The inherent single shot SNR is on the order of unity, but we have shown that 1% absorbances ($\text{SNR} = 100$) can in principle be achieved. The factors that are presently limiting further improvements in performance, and attempts to circumvent these issues, were discussed.

The experiments conducted to date have all been completed in a laboratory environment using multi-pass optics to achieve reasonable pathlength. Once acceptable performance is achieved, the next step will be to assess the coherent detection performance capability (still in terms of achievable detection sensitivity through signal averaging) in "real-world" environment with both natural and man-made targets. A calibrated portable chemical release unit will be used to generate known chemical plume releases to quantify chemical detection sensitivity. This will be done at a local LANL test range for measurements to distances up to ~ 2 Km range. The emphasis of these studies will be on understanding the impact of real world atmospheric and speckle effects.